CLAIMS

What is claimed is:

1. A method for calibrating a machine having a base, a movable element, which is movable relative to the base in reference to an axis, and a control system for numerically controlling movement of the movable element in reference to the axis along a predetermined distance, the method comprising:

identifying a plurality (N + 1) of predetermined spaced-apart positions (i) along the predetermined distance, each of the positions (i) being associated with a desired position ($DP_{r,i}$), the desired position ($DP_{r,i}$) being representative of a desired location of the movable element in the predetermined distance;

moving the movable element to each of the predetermined positions (i) in a first direction and calculating an error ($E_{r,i}$) between the desired position ($DP_{r,i}$) and an actual position ($AP_{r,i}$) of the movable element relative to the base and in reference to the axis at each of the predetermined positions (i);

translating the structure to each of the predetermined positions (i) in a second direction opposite the first direction and calculating an error ($E_{r+1,i}$) between the desired position ($DP_{r+1,i}$) and an actual position ($AP_{r+1,i}$) of the movable element relative to the base and in reference to the axis at each of the predetermined positions (i);

repeating the above two steps a predetermined number (R/2) of times;

identifying at least two sources of assignable cause error; and

quantifying the assignable cause error that is attributable to the at least two sources using at least one of the error ($E_{r,i}$) and the error ($E_{r+1,i}$).

2. The method of Claim 1, wherein the assignable cause error includes an average cumulative positioning error per unit length.

3. The method of Claim 2, wherein the average cumulative positioning error per unit length is based upon an average of the errors ($E_{r,i}$) and ($E_{r+1,i}$) at each of the predetermined positions (i) and an amount by which the movable element is moved relative to the base.

4. The method of Claim 2, further comprising calculating a cumulative capability index (Cumulative C_{pk}).

5. The method of Claim 4, wherein the cumulative capability index (Cumulative C_{pk}) is calculated as follows:

$$\text{Cumulative } C_{pk} = \frac{\text{Spec}_{\text{CUM}} - \left|\overline{X}_{CUM}\right|}{3 \times \sigma_{CUM}}$$

where: Spec_{CUM} is a predetermined constant,

$$\overline{X}_{CUM} = \frac{\sum_{i=0}^{N} \left[\frac{\sum_{r=1}^{R} E_{r,i}}{R} \right]}{(N+1)}$$

$$s_{CUM} = \sqrt{\frac{\sum_{i=0}^{N} \left[\sum_{r=1}^{R} \frac{E_{r,i}}{R} - \overline{X}_{CUM} \right]^2}{N}}$$

and

$$\sigma_{CUM} = S_{CUM} \times \sqrt{\left(1 + \frac{1}{N+1}\right)}.$$

6. The method of Claim 5, further comprising calculating a safe tolerance for cumulative error (ST_{CUM}) as follows:

$$ST_{CUM} = \pm\left(3 \times \sigma_{CUM} + \left|\overline{X_{CUM}}\right|\right).$$

7. The method of Claim 2, wherein each of the desired positions ($DP_{r,i}$) is spaced out by a predetermined distance (L).

8. The method of Claim 7, wherein the average cumulative positioning error per unit length (m) is calculated as follows:

$$m = \frac{2 \times \left[\sum_{i=0}^{N} \frac{\left\{ [E_{1,i} + E_{3,i} + \ldots + E_{(R-1),i}] + [(E_{2,i} - \overline{E}_{REV}) + (E_{4,i} - \overline{E}_{REV}) + \ldots + (E_{R,i} - \overline{E}_{REV})] \right\}}{(R)} \right]}{(L \times N)}.$$

9. The method of Claim 1, wherein the assignable cause error includes an average reversal error ($\overline{E}_{REV}$).

10. The method of Claim 9, wherein the average reversal error ($\overline{E}_{REV}$) based on an average of the differentials ($E_{r,i}$) and ($E_{r+1,i}$) at each of the predetermined positions (i) and an amount by which the movable element is moved relative to the base.

11. The method of Claim 10, wherein the average reversal error ($\overline{E}_{REV}$) is calculated as follows:

$$\overline{E}_{REV} = \frac{\sum_{i=0}^{N}\left[\frac{(E_{2,i}+E_{4,i}+\ldots+E_{R,i})}{(R/2)} - \frac{(E_{1,i}+E_{3,i}+\ldots+E_{(R-1),i})}{(R/2)}\right]}{(N+1)}.$$

12. The method of Claim 10, further comprising calculating a repeat capability index (Repeat C_{pk}).

13. The method of Claim 12, wherein the repeat capability index (Repeat C_{pk}) is calculated as follows:

$$\text{Repeat } C_{pk} = \frac{\text{Spec}_{\text{REP}} - \left|\overline{X}_{REP}\right|}{3 \times \sigma_{REP}}$$

where: Spec_{REP} is a predetermined constant,

$$\overline{X}_{REP} = \frac{\sum_{i=0}^{N}\left[\frac{\sum_{r=2}^{R}\left|E_{r,i} - E_{(r-1),i}\right|}{(R-1)}\right]}{(N+1)}$$

$$s_{REP} = \sqrt{\frac{\sum_{i-0}^{N}\left[\sum_{r=1}^{R}\frac{\left|E_{r,i} - E_{(r-1),i}\right|}{(R-1)} - \overline{X}_{REP}\right]^2}{N}}$$

and

$$\sigma_{REP} = S_{REP} \times \sqrt{\left(1 + \frac{1}{N+1}\right)}.$$

14. The method of Claim 13, further comprising calculating a safe tolerance for repeatability error (ST_{REP}) as follows:

$$ST_{REP} = \pm\left(3 \times \sigma_{REP} + \left|\overline{X}_{REP}\right|\right).$$

15. The method of Claim 1, wherein the assignable cause error includes home positioning error.

16. An apparatus for calibrating a machine having a base, a movable element that is movable relative to the base in reference to an axis, and a control system for numerically controlling movement of the movable element along the axis, the apparatus comprising:

means for calculating an error ($E_{r,i}$) between a desired position ($DP_{r,i}$) and an actual position ($AP_{r,i}$) of the movable element relative to the base and in reference to the axis at each of a plurality of predetermined positions (i) when the movable element is moved relative to the base in a first direction;

means for calculating an error ($E_{r,i}$) between a desired position ($DP_{r,i}$) and an actual position ($AP_{r,i}$) of the movable element relative to the base and in reference to the axis at each of the predetermined positions (i); and

means for quantifying an assignable cause error that is attributable to at least two sources, the quantifying means employing at least one of the error ($E_{r,i}$) and the error ($E_{r+1,i}$) to quantify the assignable cause error attributable to each of the at least two sources.

17. A method for calibrating a machine having a base, a movable element, which is movable relative to the base in reference to an axis, and a control system for numerically controlling movement of the movable element in reference to the axis along a predetermined distance, the method comprising:

identifying a plurality (N + 1) of predetermined spaced-apart positions (i) along the predetermined distance, each of the positions (i) being associated with a desired position ($DP_{r,i}$), the desired position ($DP_{r,i}$) being representative of a desired location of the movable element in the predetermined distance;

moving the movable element to each of the predetermined positions (i) in a first direction and calculating an error ($E_{r,i}$) between the desired position ($DP_{r,i}$) and an actual position ($AP_{r,i}$) of the movable element relative to the base and in reference to the axis at each of the predetermined positions (i);

translating the structure to each of the predetermined positions (i) in a second direction opposite the first direction and calculating error ($E_{r+1,i}$) between the desired position ($DP_{r+1,i}$) and an actual position ($AP_{r+1,i}$) of the movable element relative to the base and in reference to the axis at each of the predetermined positions (i);

repeating the above two steps a predetermined number (R/2) of times; and

determining an average cumulative positioning error per unit length (m) based upon an average of the differentials ($E_{r,i}$) and ($E_{r+1,i}$) at each of the predetermined positions (i) and an amount by which the movable element is moved relative to the base.

18. The method of Claim 17, further comprising the step of determining an average reversal error ($\overline{E}_{REV}$) based on an average of the differentials ($E_{r,i}$) and ($E_{r+1,i}$) at each of the predetermined positions (i) and an amount by which the movable element is moved relative to the base.

19. The method of Claim 18, wherein the average reversal error ($\overline{E}_{REV}$) is calculated as follows:

$$\overline{E}_{REV} = \frac{\sum_{i=0}^{N}\left[\frac{(E_{2,i} + E_{4,i} + \ldots + E_{R,i})}{(R/2)} - \frac{(E_{1,i} + E_{3,i} + \ldots + E_{(R-1),i})}{(R/2)}\right]}{(N+1)}.$$

20. The method of Claim 19, further comprising calculating a repeat capability index.

21. The method of Claim 20, further comprising calculating a safe tolerance for repeatability error.

22. The method of Claim 17, further comprising calculating a cumulative capability index.

23. The method of Claim 22, further comprising calculating a safe tolerance for cumulative error.

24. The method of Claim 17, further comprising the step of calculating a home error (E_H).

25. The method of Claim 24, wherein the home error (E_H) is calculated as follows:

$$E_H = \frac{\{[E_{1,0} + E_{3,0} + \ldots + E_{(R-1),0}] + [(E_{2,0} - \overline{E}_{REV}) + (E_{4,0} - \overline{E}_{REV}) + \ldots + (E_{R,0} - \overline{E}_{REV})]\}}{(R)}.$$

26. The method of Claim 17, further comprising calculating a position capability index.

27. The method of Claim 26, further comprising calculating a safe tolerance for position error (ST_{POS}).